ELIMINATION OF POLARIZATION FADING IN UNBALANCED OPTICAL
MEASURING INTERFEROMETERS

This invention is related to a method and an assembly
for the elimination of polarization fading in unbalanced
5   optical measuring interferometers.

BACKGROUND OF THE INVENTION
An optical interferometer is an optical transmission
network that produces interference between different
portions of optical radiation that have traveled different
10 paths through the network. In an unbalanced optical
interferometer the time delay in the two optical paths are
different by an amount τ. The output intensity from such an
interferometer will have a periodic dependence called
fringes of the output intensity that is periodic versus the
15 interferometer phase delay $\phi=2\pi\nu\tau$, where ν is the optical
frequency launched into the interferometer. Information
about the path delay difference, the input optical
frequency, or the input optical frequency spectrum may thus
be deduced from the output interference signal.
20   An optical interferometer network may also contian more
than one pair (or set) of paths from the input to the output
port. Different pairs (or sets) of paths may then be
interpreted as different interfereometers. The interference
caused by individual interferometers may be interogated
25 separately,
a.   by assigning a specific range of optical wavelengths,
     thus employing a wavelength division multiplexing (WDM)
     technique,
b.   by assigning a specific range of total transmission
30   time delay to the paths assosciated with each
     interferometer, thus employing a time division
     multiplexing (TDM) technique,
c.   or by assigning a specific combination of input and
     output ports to the paths assosciated with each
35   interferometer, thus employing a space division
     multiplexing (SDM) technique. An SDM system may for
     instance be interrogated by using optical switches to

access different combinations of input and output ports
sequentially, or by splitting the optical radiation
from a single interrogation source into different
interferometer sub-networks, and connecting one
5   detector to the output of each sub-network.
Network interrogation employing combinations of WDM, TDM and
SDM is also possible.

The visibility or amplitude of the output fringes
depends on the states of polarization (SOPs) of the two
10   interfering signals, which we will label SOP1 and SOP2. In
many interferometers SOP1 and SOP2 will vary randomly with
time due to changes in the input SOP or in the birefringence
properties of the two optical pathways. The fringe
visibility is proportional to the projection of SOP1 onto
15   SOP2. The reduction of fringe visibility with reduced
projection of the SOPS is called polarization fading, and
generally causes a reduced signal to noise ratio in the
interferometer readout. Especially, the situation with SOP1
⊥ SOP2 (orthogonal SOPs) causing total polarization fading
20   with zero visibility should be avoided. When the fading is
total, the interferometer output will not carry any
information about v or t at all.

Several methods for reduction or elimination of the
polarization fading problem are known. One known method uses
25   Faraday rotating mirrors, as disclosed by A.D. Kersey et.
al. in ["Polarisation insensitive fibre optic Michelson
interferometer", El. Lett., Vol. 27, pp. 518-19, 1991]. This
method allows for a simple source and detection system, but
it works only for the Michelson interferometer
30   configuration. Furthermore, the Faraday rotating mirrors may
be expensive, space consuming, and sensitive to extreme
thermal, electromagnetic and other environmental conditions.

Other known methods are based on active polarization
control at the input, as disclosed by A. D. Kersey et. al.
35   in ["Optimization and Stabilization of Visibility in
Interferometric Fiber-Optic Sensors Using Input-Polarization
Control", J. of Lightwave Technol., Vol. 6, pp. 1599-1609,
1988], or the use of a polarizer combined with active
polarization control at the output end, as disclosed by K.

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H. Wanser et. al. in ["Remote polarization control for
fiber-optic interferometers ", Opt. Lett., Vol. 12, pp. 217-
19, 1987]. In both cases the polarization controller is
continuously adjusted to optimize the fringe visibility.
5   These techniques require relatively complex systems to
provide feedback signals to the polarization controller, and
in systems with spatial division multiplexing (SDM) or
wavelength division multiplexing (WDM) of multiple sensors,
individual polarization controllers for each sensor are
10 generally required. The polarization modulator used for the
polarization control must be capable of modulating the SOP
in three dimensions on the Poincarè sphere. This generally
implies that the polarization modulators at least must be of
the "dual stage" type. Dual stage polarization modulators
15 generally incorporate two independently adjustable
birefringent elements, and are thus more complex and
expensive than single stage modulators having only one
adjustable birefringent element.
        Still other known methods are based on modulating the
20 input SOP between three states, as disclosed by A. D. Kersey
et. al. in ["Input polarisation scanning technique for
overcoming polarisation-induced signal fading in
interferometric fiber sensors ", El. Lett., Vol. 24, pp.
931-33, 1988] and in [US Patent No. 4 932 783], or on the
25 use of three detectors at the output with three polarizers
that are adjusted to monitor different polarization states,
as disclosed by N. J. Frigo et. al. in ["Technique for
elimination of polarisation fading in fibre
interferometers", El. Lett., Vol. 20, pp. 319-20, 1984].
30 These techniques increase the complexity of the processing
by requiring simultaneous processing of three fringe
signals, especially in WDM systems where separate receivers
are required for each WDM channel. They also increase the
complexity of the hardware by either requiring a dual stage
35 polarization modulator, or three detectors and polarizers.
        Another known method is based on the use of a pulsed
source and a compensating interferometer which incorporates
a polarization maintaining coupler, a standard coupler, and
a polarization modulator, as disclosed by B. Y. Kim et. al.

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in [US Patent No. 5 173 743]. This method may be attractive
when applied to time division multiplexed (TDM) ladder
sensor networks. However, the compensating interferometer
increases the complexity of the interrogation, and 3 dB of
5 source power is lost in the output coupler from the
compensating interferometer. If the network is not of the
ladder type, another 3 dB of optical power will be
effectively lost at the detector, since only one half of the
detected pulses will carry useful information. Another
10 problem with this method is that the readout phase from the
interferometer is sensitive to birefringence changes in the
lead fiber between the source and the interferometers.
    One sensor configuration of special interest is that of
a WDM fiber-optic interferometric sensor system employing
15 two identical wavelength selective low reflectivity fiber
Bragg grating reflectors to define the two paths of each
sensor interferometer. For instance, a Fabry-Perot
interferometer can be formed by writing two identical Bragg
gratings into the core of a single optical fiber at
20 different locations. Different reflection bands should be
dedicated to each sensor, so that information about the
individual sensors can be accessed by use of a multi-
wavelength source at the network input producing coherent
light at each sensor wavelength, and a wavelength division
25 multiplexer at the network output, that directs the
interference signal from each sensor to a dedicated
detector.

OBJECTIVE
    The main objective of the present invention is to
30 provide a simple and practical method and assembly, with
reduced complexity compared to existing techniques, which
eliminates or reduces the probability for polarization
induced fading in optical interferometers. This objective
implies that the output signals from the interferometer
35 always should carry the information required to determine
the difference in optical path length, or optical phase,
between two different paths through the interferometer.
    A second objective of the present invention is to

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provide a method and assembly which allows the readout
interferometer phase to be insensitive to birefringence
changes in the lead fiber between the source and the
interferometer.

5   A third objective of the present invention is to
provide a method and assembly which can be applied to
interrogation of any types of unbalanced interferometer that
do not contain polarization selective components, such as
polarizers or polarization beam splitters. This class of

10   interferometers includes variants of the Fabry-Perot,
Michelson, and Mach-Zender topologies. The method should
also be applicable in interrogation systems where a pulsed
source and a compensating interferometer is used to
compensate out the imbalance of the interrogated

15   interferometer(s).

        A fourth objective of the present invention is to
provide a method and assembly which can be applied to
interrogation of wavelength division multiplexed (WDM),
space division multiplexed (SDM), and time division

20   multiplexed (TDM) interferometer networks, including TDM
ladder networks.

        A specific objective of the present invention is to
provide a method and assembly which can be applied to
interrogation of fiber optic wavelength division multiplexed

25   sensor systems employing wavelength selective Bragg
reflectors in the sensing interferometers and a multi-
wavelength source, which requires only one polarization
modulator for the entire system, and only one detector
dedicated to the monitoring of each sensor.

30   A general objective of the present invention is to
provide a method and assembly that overcomes limitations set
by other known methods.

SUMMARY OF THE INVENTION

        The objective of the invention is achieved with a

35   method having features as stated in claims 1 and 8. Further
features are stated in the dependent claims.

        The main part of the invention is characterized in that
the polarization state of the optical power launched into an

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interferometer network is modulated at a frequency
comparable to or higher than the inverse of the difference
in transmission time delay between the two optical paths
through the interferometer. A control and signal processing
5   unit extracts several interference signals detected at the
output of the interferometer network in at least two time
slots, that are positioned in time at certain time delays
(or phases) relative to the input polarization modulation
period. The time slots should be chosen such that the two
10 optical signals interfering at the output port after having
traveled the two paths through the interferometer, originate
from different combinations of input polarization states in
each time slot, and such that total polarization fading of
the interference visibility never will occur simultaneously
15 in all time slots. Minimization of the sensitivity of the
readout interferometer phase to birefringence changes in the
path from the interrogating optical source to the
interferometer may be achieved by modulating the input
polarization between two orthogonal polarization states and
20 by processing signals from four distinct time slots.

DETAILED DESCRIPTION OF THE INVENTION
        The invention will be described below with reference to
the accompanying drawings illustrating the invention by way
of examples.
25 Fig. 1   illustrates a preferred embodiment of this
                invention, including the interrogated
                interferometer network (3) including a Fabry-Perot
                interferometer.
    Fig. 2   illustrates a typical evolution of the input and
30   output states of polarizations (SOPs) versus time.
    Fig. 3   illustrates alternative embodiments of the
                interferometer network (3) in Fig. 1,
                incorporating a Michelson interferometer in Fig. 3
                (a) and a Mach-Zender interferometer in Fig. 3
35   .(b).
    Fig. 4   illustrates an alternative embodiment of the
                invention, demonstrating interrogation of multiple
                wavelength division multiplexed interferometers.

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In the preferred embodiment of this invention,
illustrated in Fig. 1, an optical source (1) launches
coherent optical radiation into the fiber-optic sensor
network (3) through a polarization modulator (2). The sensor
network (3) consists of an input-output optical coupler (4)
with a 50% power splitting ratio, a lead fiber (5) and a low
finesse Fabry-Perot (FP) interferometer (6) consisting of
two reflectors (7,8) and a fiber delay line (9) with dual-
pass delay τ. The power reflectivities of (7) and (8) should
preferably be small (<10%), allowing multiple mirror
reflections to be neglected. The output power from the
network (3) is guided to a photo-detector, and the resulting
analog electrical signal is transferred to the analog-to-
digital conversion interface of a control & signal
processing unit (11), which is responsible for processing
the detected signals electronically to extract the
interferometer phase information, and for transferring this
information in a suitable form to the end user.

The control & signal processing unit (11) also controls
the polarization modulator (2) and causes the input
polarization state SOP0 launched into (3) to switch between
two orthogonal states, denoted SOP0a and SOP0b in Fig. 2.
The polarization switching period should equal 4τ, and the
duty-cycle of the modulation should be 50%, as illustrated
by the top curve in Fig. 2. The coupler (4), the lead fiber
(5), the interferometer fiber (9), and the reflectors (7,8)
should have negligible polarization dependent losses. The
latter condition implies that the polarization states SOP1
and SOP2 reflected from (7) and (8), respectively, and
interfering at the left hand side of (7) in Fig. 1, will
also both be switching between two orthogonal states,
denoted SOP1A, SOP1B, SOP2A, and SOP2B in Fig. 2. SOP1A and
SOP1B may then generally be written in a Jones-vector
notation as

$$SPO1A = \vec{A} = K_1 \begin{vmatrix} \cos(\alpha) \\ \sin(\alpha)\, e^{i\gamma} \end{vmatrix} \qquad SPO1B = \vec{B} = K_1 \begin{vmatrix} \cos(\alpha)\, e^{-i\gamma} \\ \sin(\alpha) \end{vmatrix}$$

where the vector elements are chosen to represent the
projections of the fields onto the orthogonal eigen-
polarization states of the interferometer. By the
interferometer eigen-polarization states we mean the
5   orthogonal output SOPs generated when the SOP0 is adjusted
so that SOP1 = SOP2. K_1 depends on the source power, and the
losses in the transmission through (4,5,9) and in the
reflections (7,8), while α and γ are angles that depend on
the birefringence properties of the lead fiber (5).
10   The chosen polarization projection states allow SOP2A
and SOP2B to be written on the form

$$SPO2A = J\bar{A} = K_2 e^{i\phi}\begin{bmatrix} \cos(\alpha) \\ \sin(\alpha)\,e^{i\gamma+\theta} \end{bmatrix} \qquad SPO2B = J\bar{B} = K_2 e^{i\phi}\begin{bmatrix} \cos(\alpha)\,e^{-i\gamma} \\ \sin(\alpha)\,e^{i\theta} \end{bmatrix}$$

where the Jones matrix

$$J = e^{i\phi}\begin{bmatrix} 1 & 0 \\ 0 & e^{i\theta} \end{bmatrix} \qquad\qquad (1)$$

essentially describes difference between the SOP changes
from SOP0 to SOP1 and that from SOP0 to SOP2. $\phi = 2\pi\nu\tau$ is the
15   interferometer phase that we want to measure, ν is the
optical frequency, and θ is the birefringent phase-shift
between the eigen-polarization states of the interferometer.
K_2 depends on losses in the transmissions and reflections of
the system.
20   The two lower curves in Fig. 2 illustrate the switching
of SOP1 and SOP2. A periodic pattern consisting of 4 time
slots can be observed, where:
   - SOP1A interferes with SOP2A in slot1,
   - SOP1B interferes with SOP2A in slot2,
25   - SOP1B interferes with SOP2B in slot3,
   - SOP1A interferes with SOP2B in slot4.
The interference power will be composed by one term that
depends on ϕ, θ, γ, and α, and one term that is independent on

these parameters. The power from each time slot n will
produce an electrical signal, S_n at the detector output, which
is proportional to the interference power. Based on the
given conditions, it can be shown that

$$S_1 = 2K_3 Re(\vec{A}^+ \boldsymbol{J}\vec{A}) = a\cos(\phi_1)$$
$$S_2 = 2K_3 Re(\vec{B}^+ \boldsymbol{J}\vec{A}) = a\cos(\phi_2)$$
$$S_3 = 2K_3 Re(\vec{B}^+ \boldsymbol{J}\vec{B}) = a\cos(\phi_3)$$
$$S_4 = 2K_3 Re(\vec{A}^+ \boldsymbol{J}\vec{B}) = a\cos(\phi_4)$$

(2)

5 where K_3 accounts for the detector responsivity and losses in
(4,5), superscript $^+$ indicates conjugate transpose,

$$\phi_1 = \phi + \theta + \varphi$$
$$\phi_2 = \phi + \theta/2 + \gamma - \pi/2$$
$$\phi_3 = \phi - \theta \qquad , and \quad a^2 + b^2 = K_1 K_2 K_3^2.$$
$$\phi_4 = \phi + \theta/2 - \gamma - \pi/2$$

(3)

φ is a function of θ and α.

The control & processing unit extracts the signals S_1
through S_4 and processes them to determine the phases ϕ_1
10 through ϕ_4. Note that the detected signals are delayed
relative to the control signals supplied to the polarization
modulator. Some calibration of the input slot timing is
therefore required. Several methods are known for phase
reconstruction without ambiguity from interference signals,
15 as disclosed for instance by I. J. Bush in ["High
performance interferometric demodulation techniques", SPIE
Proc., Vol. 1795, pp. 412-20, 1992]. Generally, these
methods require means for modulating the interference phase
to generate in-phase and quadrature information from
20 interference fringes. In the preferred embodiment of the
present invention this can be achieved by modulating the
phase of the source radiation at a frequency that is an odd
harmonic of $1/(4\tau)$.

We see from (Eq. 2) that the detected fringe amplitudes
25 equal a in slots 1 and 3, and b in slots 2 and 4. Since
$a^2 + b^2 = K_1 K_2 K_3^2$ according to (Eq. 3), there can never be fading

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simultaneously in two neighboring time slots, and the sum of
the signal to noise ratios of two neighboring time slots,
limited by the fringe amplitude, will be independent on the
birefringence parameters θ, γ, and α. Thus, the main objective
5 of the present invention is satisfied.

It remains to combine the information carried by
ϕ_1, ϕ_2, ϕ_3, and ϕ_4 into one single estimate for the
interferometer phase delay, which according to (Eq. 1) is ϕ
for one eigen-polarization and $\phi+\theta$ for the other eigen-
10 polarization. In the preferred embodiment, the estimator

$$\Phi = \frac{a^2(\phi_1+\phi_2) + b^2(\phi_3+\phi_4)}{a^2+b^2} \qquad (4)$$

is computed by the control & processing unit to estimate the
interferometer phase delay. By combining (Eq. 3) and (Eq. 4)
we see that Φ in the absence of noise equals $\phi+\theta/2$, which is
15 exactly the mean of the two eigen-polarization phase delays.
Φ is independent on the birefringence parameters γ and α of
the lead fiber, and thus the second objective of the present
invention is satisfied. The weighting in (Eq. 4) of $\phi_1+\phi_2$ and
$\phi_3+\phi_4$ by a^2 and b^2, respectively, ensures that the signal to
20 noise ratio of the estimator always will be close to a
maximum.

The present invention may be implemented for
interrogation of any types of unbalanced interferometer
networks that do not contain polarization selective
25 components such as polarizers or polarization beam
splitters. As one example, Fig. 3 (a) illustrates a network
incorporating a Michelson interferometer, which may replace
the network (3) in Fig. 1 in a second embodiment of the
present invention. SOP0 is launched into the input/output
coupler (4) and the lead fiber (5), having the same
30 functions as in Fig. (1). The Michelson interferometer (12)
is formed by an optical coupler (13) splitting the optical
power from (5) into two delay arms, with reflectors (14,15)
positioned at different distances from (13) so that the dual
path time delays experienced by the two reflected signals

recombined in (13) differ by τ. SOP1 and SOP2 in this case
refer to the polarization states recombined in (13) after
returning from the short delay arm with reflector (14) and
the long delay arm with reflector (15), respectively.

5   As another example, Fig. 3 (b) illustrates a network
incorporating a Mach-Zender (MZ) interferometer, which may
replace the network (3) in Fig. 1 in a third embodiment of
the present invention. This system has separate input (16)
and output (22) lead fibers. SOP0 is launched into (16). The
10 MZ interferometer (17) is formed by an optical coupler (18)
splitting the optical power from (16) into two delay arms
(19,20). The signals emerging from (19) and (20) are
combined in a second optical coupler (21). The single pass
time delays between (18) and (21) through (19) and (20)
15 should differ by τ. SOP1 and SOP2 in this case refer to the
polarization states entering (21) from the short (19) and
long (20) arms, respectively.

      Fig. 4 illustrates a fourth embodiment of the present
invention capable of wavelength division multiplexing of
20 several wavelength selective interferometers. In the
illustrated example, a multi-wavelength source (23) is used,
launching coherent radiation at three sensor interrogation
wavelengths λ_1, λ_2, and λ_3 through the polarization modulator
(2) into the interferometer network (24). The input
25 polarization of all wavelengths is switched simultaneously
between orthogonal states, in the same way as explained for
SOP0 in the preferred fifth embodiment of the present
invention. The network contains an input/output coupler (4),
a lead fiber (5) and three FP-interferometers with
30 approximately equal dual-pass delay τ. Each FP-
interferometer consists of two identical Bragg gratings,
denoted (25), (26) or (27), causing a weak reflection in a
narrow band around the respective sensor interrogation
wavelength λ_1, λ_2, or λ_3. Each sensor grating pair should
35 produce negligible reflections at the interrogation
wavelengths of the other sensors. A wavelength division
demultiplexer (28) is connected to the output branch of (4),
distributing the interference signals from the different

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interferometers to different detectors (29, 30, 31). The
control & processing unit (32) processes the three detector
signal sequences in parallel in the same way as explained
for the single processing channel in the first preferred

5   embodiment, to extract the individual interference phases of
the three interferometers and present this information for
the end user.

The network (23) in Fig. 4 can be interrogated by a
time division multiplexing (TDM) approach using the present

10   invention, provided that all reflectors reflect the same
wavelength, i.e. either $\lambda_1 = \lambda_2 = \lambda_3$, or the gratings must be
replaced with broad-banded reflectors, and that the dual
pass delays from the input/output (4) to the beginning of
the different interferometers all are separated by at least

15   in the order of 3τ. In this case, a possible fifth
embodiment of the present invention uses a pulsed single
wavelength source at wavelength λ_1, and only one detector
without any wavelength demultiplexer in front, like the
detector (10) in Fig. 1. The source and polarization

20   modulator produces pulses with a duration of minimum 2τ,
with polarization state switching between orthogonal
polarizations within each pulse at a frequency that is an
odd harmonic (or multiple) of 1/(4τ) and which is higher
than the inverse pulse duration, like illustrated for SOP0

25   in Fig. 2. The detected signal will consist of one time
sequence for each pulse transmitted from the source, each
sequence containing at least four time-slots originating
from each sensor interferometer. The time slots contain
information about the interference phases of individual

30   sensors, encoded in the same way as for the output time-slot
signals described in the first preferred embodiment. The
control and processing unit may thus extract the
interference phases by separating, identifying and
processing the information originating from each sensor in

35   the same way as described for the first preferred
embodiment.

A special case of TDM interferometer networks are
ladder interferometer networks, with geometries of the type

described in [US Patent No. 5 173 743, Fig.1, items (26),
(27 a, b, c, d), (28), and (31 a, b, c, d)]. In the ladder
networks, the input to output delay of a number N of
interferometer arms are equally spaced by the amount τ, and
5   all paths, except for two, are thus part of two
interferometers at the same time. The current invention can
be used for interrogation of such ladder networks,
including a compensating interferometer with imbalance τ
placed after the source, as illustrated in [US Patent No. 5
10 173 743, Fig.1, items (20, 21, 22, 23, 25)]. Each pulse from
the source should have duration equal to τ, and will thus be
split into two by the compensating interferometer. The
polarization modulator can be placed between the
compensating interferometer and the network. Polarization
15 maintaining fibers and couplers should be used in the
compensating interferometer to ensure that the polarization
states of the two consecutive pulses emerging from the
compensating interferometer will be switching between
identical pairs of orthogonal polarization states.
20 Alternatively, an imbalanced Michelson interferometer with
Faraday-rotating mirrors, and otherwise standard fibers and
couplers, may be used as the compensating interferometer.

The current invention may be used for interrogation of
such ladder networks, without the inclusion of any
25 compensating interferometer. The duration of each pulse from
the source should in this case be close to 2τ.

Although coherent sources have been assumed in all the
previous examples, the present invention can also be used in
a white-light interferometer that are interrogated by
30 scanning the path-imbalance of a compensating
interferometer.